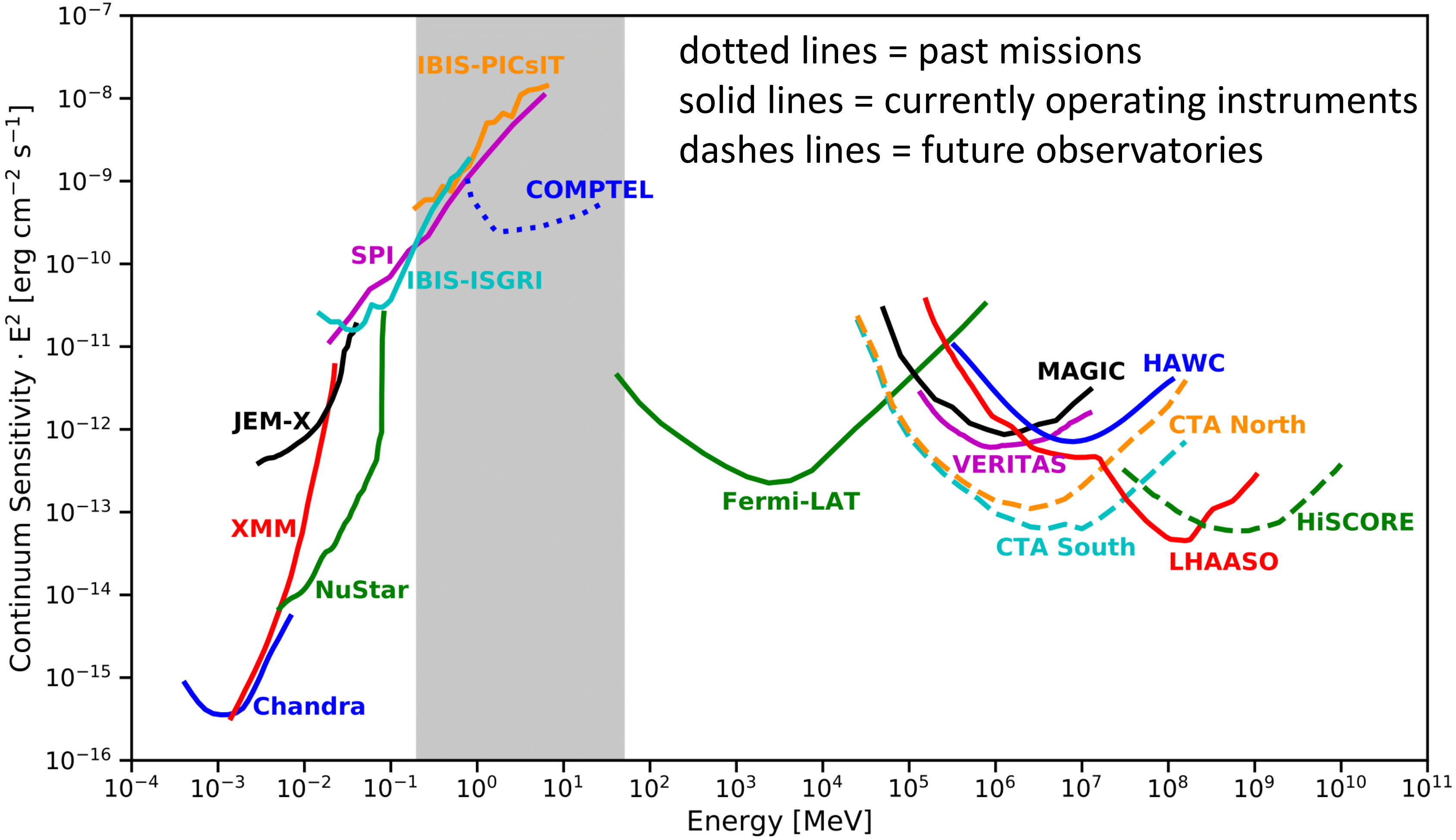
Introducing the MeVCube concept: a CubeSat for MeV observations

Giulio Lucchetta
Monitoring the high-energy sky with small satellite
Brno, 07/09/2022

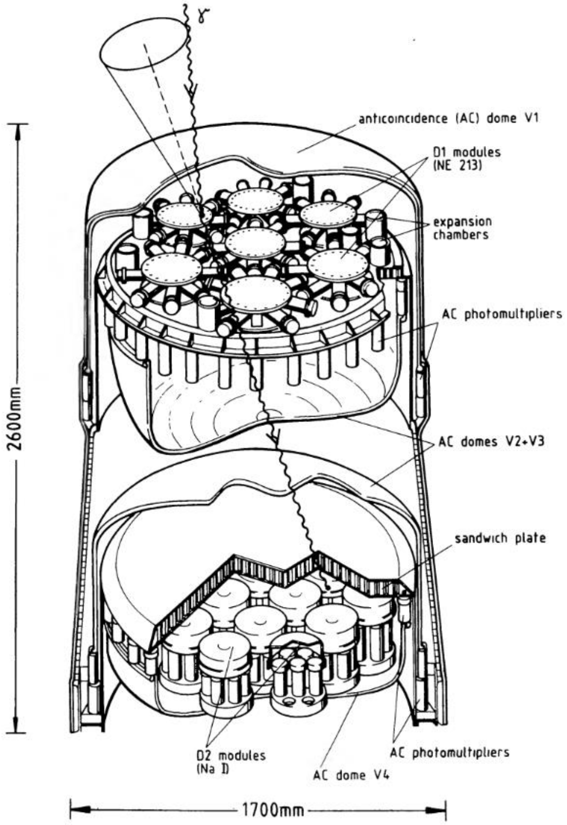
IFAE
25 years 1991-2016
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

Introduction: the “MeV gap”



➢Science case: study of the emission mechanisms in AGNs and blazars, GRBs and search of electromagnetic counterparts of GW events, nuclear astrophysics, and more…

Compton telescopes: past and future



COMPTEL (1991-2000)

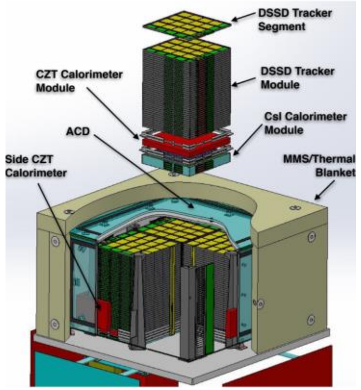
- ✓ Height: 2.6m, diameter: 1.7m, weight: 1500kg
- ✓ Technology based on scintillators
- ✓ Energy range from 0.75 to 30 MeV
- ✓ Catalogue: 32 steady sources, 31 GRBs

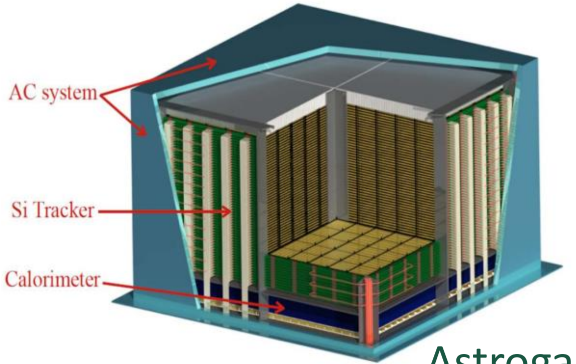
~1.5m x 1.5m

Payload size

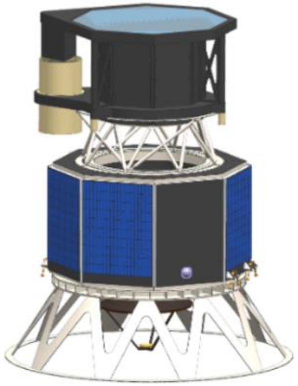
~50cm x 50cm

AMEGO



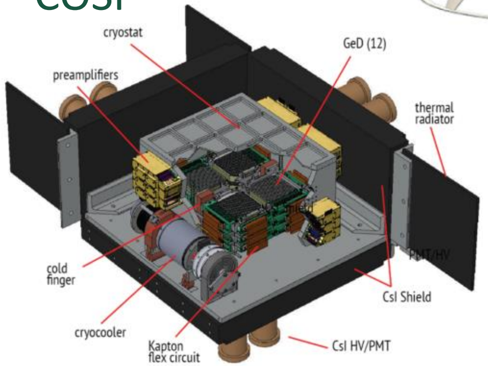


Astrogam

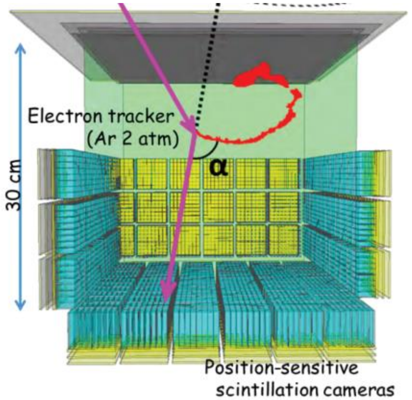


GECCO

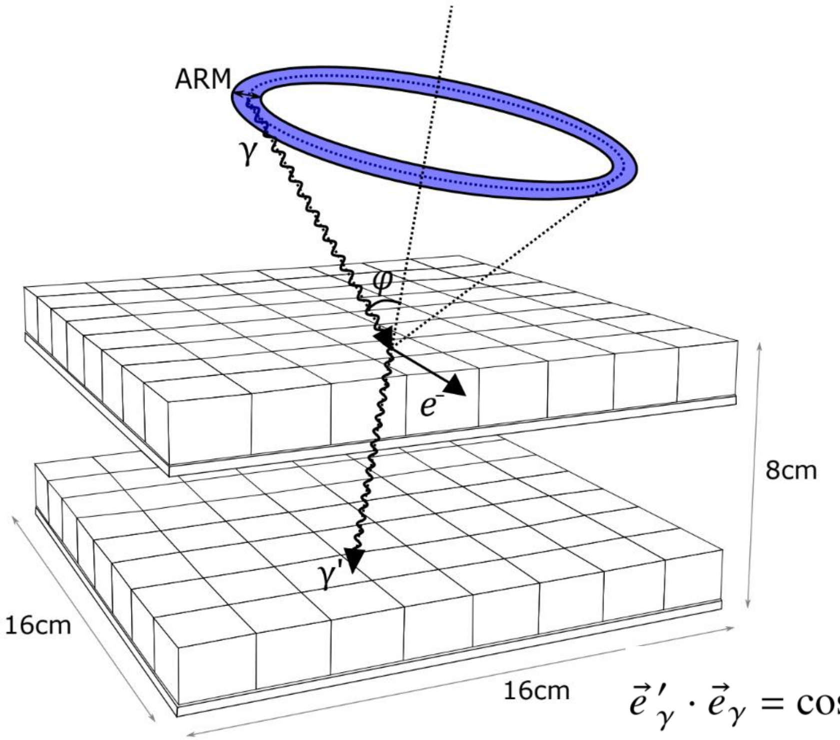
COSI



SMILE-2+/ ETCC



MeVCube concept



$$\vec{e}\,'_\gamma \cdot \vec{e}_\gamma = \cos\varphi = 1 - \frac{m_e c^2}{E'_\gamma} + \frac{m_e c^2}{E'_\gamma + E'_e}$$

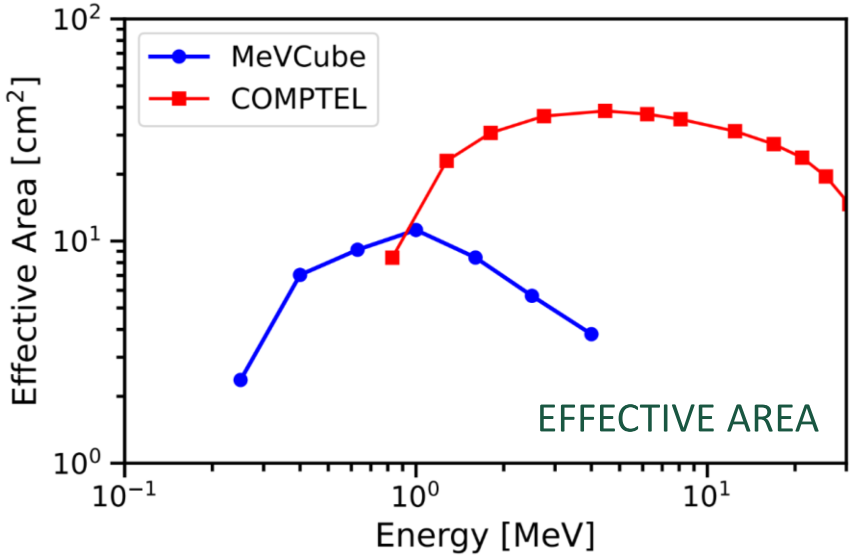
- ✓ Compact Compton telescope on a CubeSat: 4U for the scientific payload, 2U for the satellite bus (6U total)
- ✓ 128 pixelated Cadmium Zinc Telluride (CdZnTe or CZT) detectors, on two layers (+ ACD to veto charged particle background)
- ✓ High atomic number (48,30,52) and density ($5.8 g/cm^3$): good stopping power
- ✓ Good spectral and imaging performance

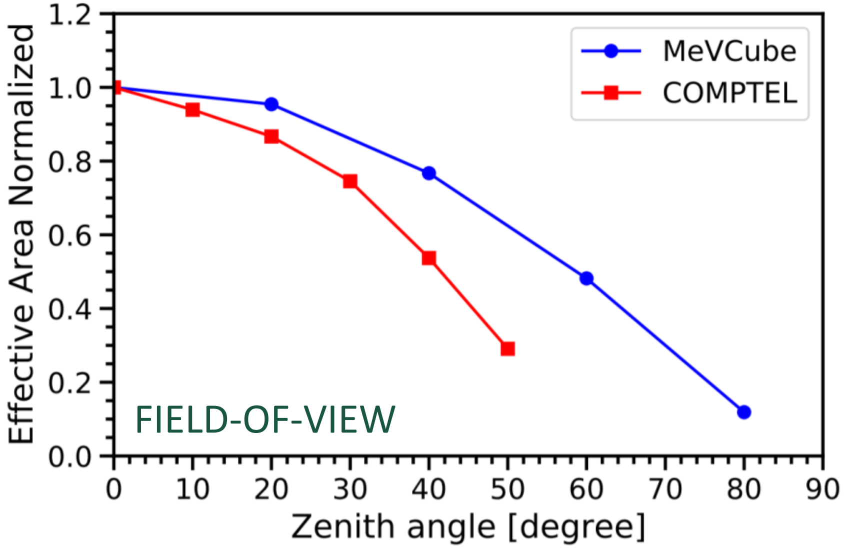
Parameter	Design value
CubeSat model	4 U scientific payload, 6 U complete satellite
Orbit	Low Earth Orbit (LEO), $\sim$ 550 km altitude, $\leq 5°$ inclination
Number of CdZnTe detectors	128
CdZnTe detector size	2.0 cm $\times$ 2.0 cm $\times$ 1.5 cm
Pixel pitch	2.45 mm
Pixel size	2.25 mm $\times$ 2.25 mm
Depth resolution (FWHM)	$\sim$ 1.8 mm
Energy resolution (FWHM)	$\sim$ 6.5% at 200 keV, $\sim$ 2.8% at 662 keV, $\lesssim$ 2.0% at $>$ 1 MeV
Read-out electronics	VATA450.3
Total power consumption	$<$ 5 W

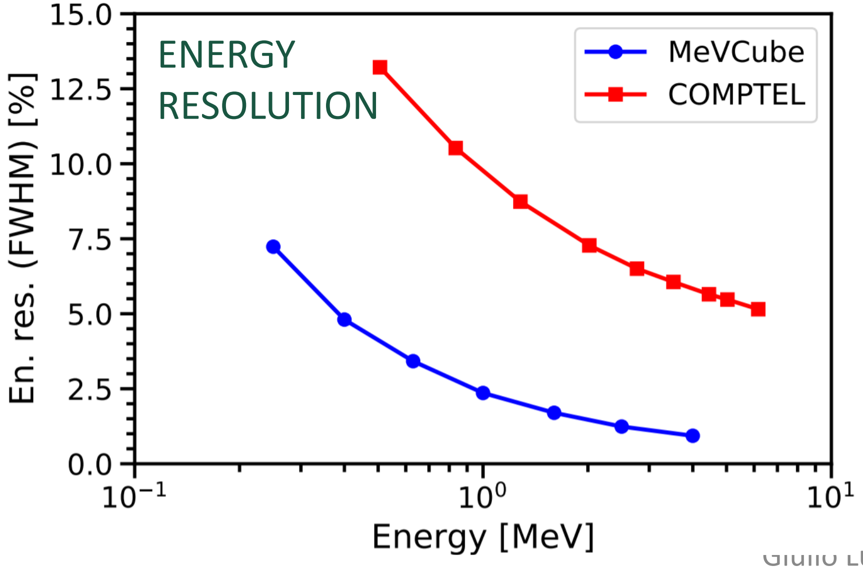
- ✓ Performance of the full telescope evaluated through simulations (Geant4 based simulation toolkit *MegaLib*: Zoglauer et al., *New Astron. Rev.*, 50, 2006)
- ✓ Requirements for single CZT detectors validated by laboratory measurements

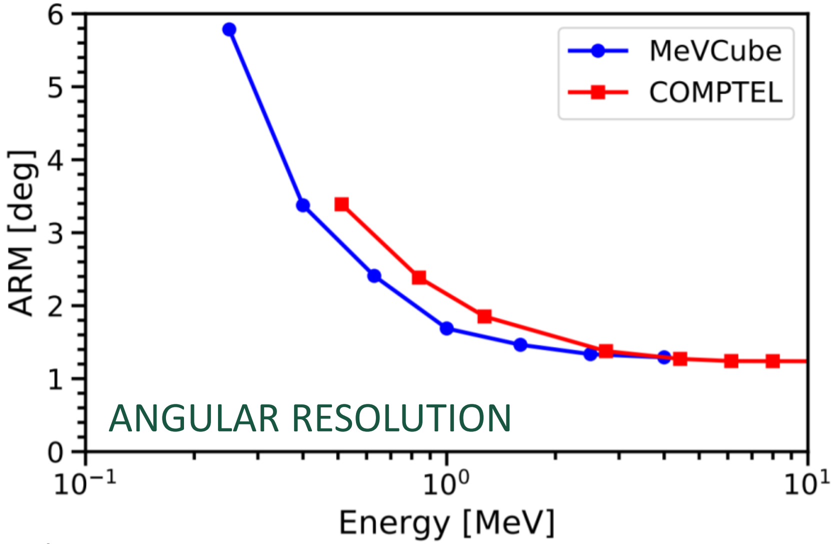
Institut de Física d'Altes Energies

MeVCube performance



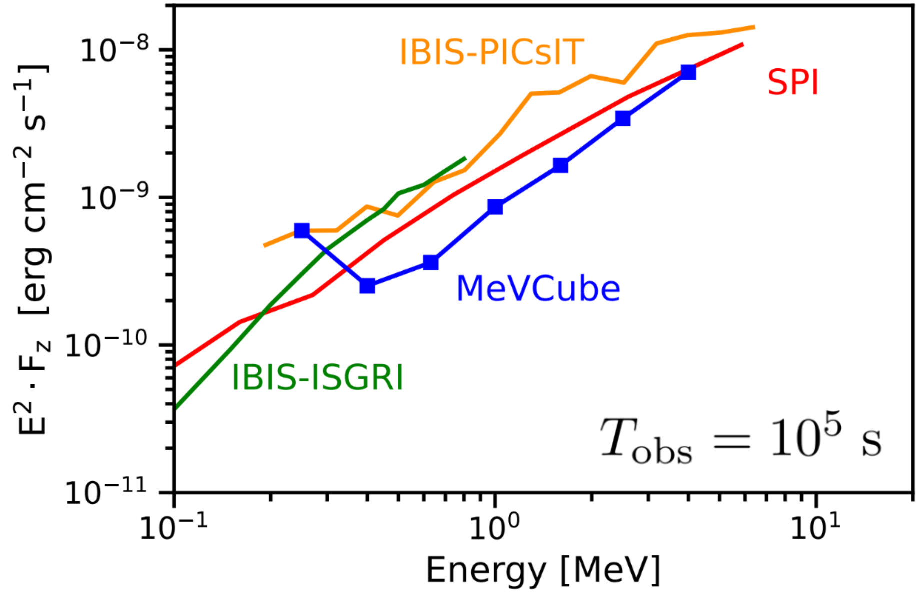


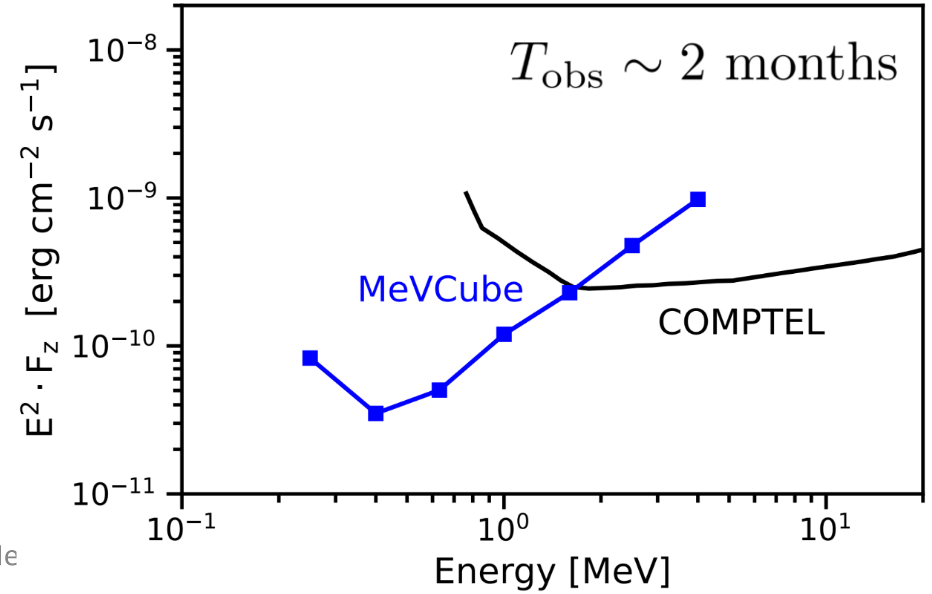




MeVCube sensitivity

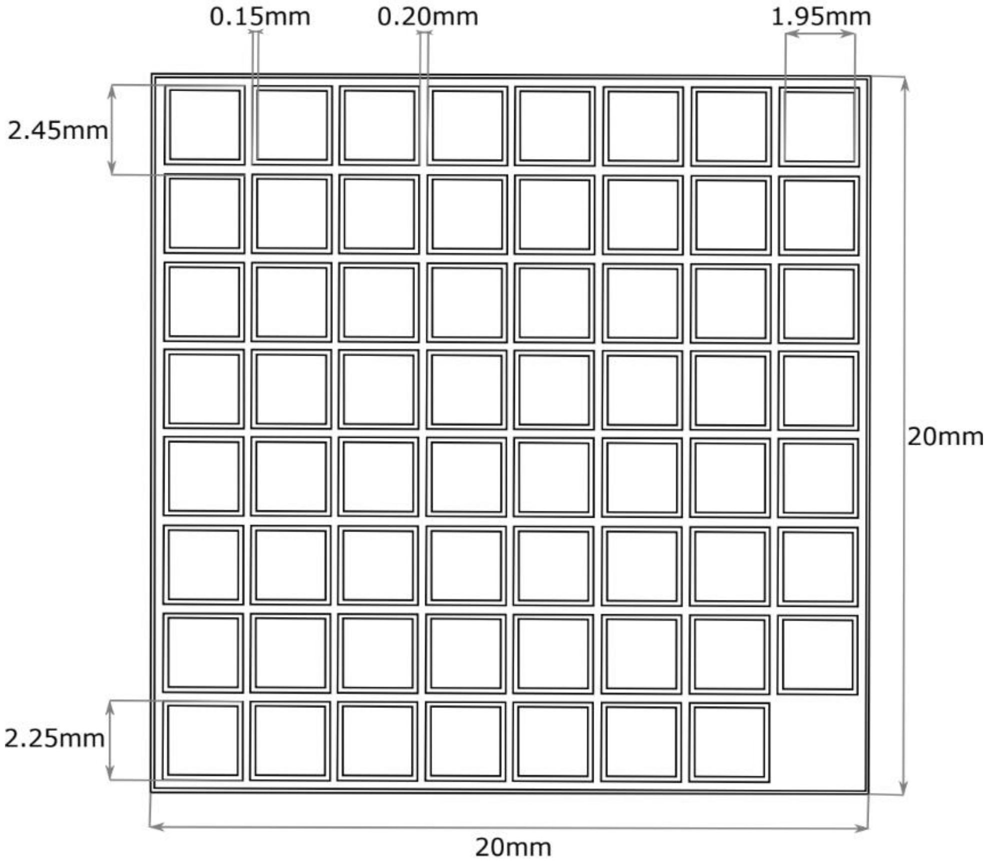
- Minimum flux that is likely to result in a statistically significant source detection
- Calculated based on instrument performance for angular resolution, effective area, observation time and background rate
- MeVCube sensitivity evaluated for a 3σ detection of a source at high Galactic latitude
- Background model adapted from [Cumani et al., *Exper.Astron., 47 (2019)*]





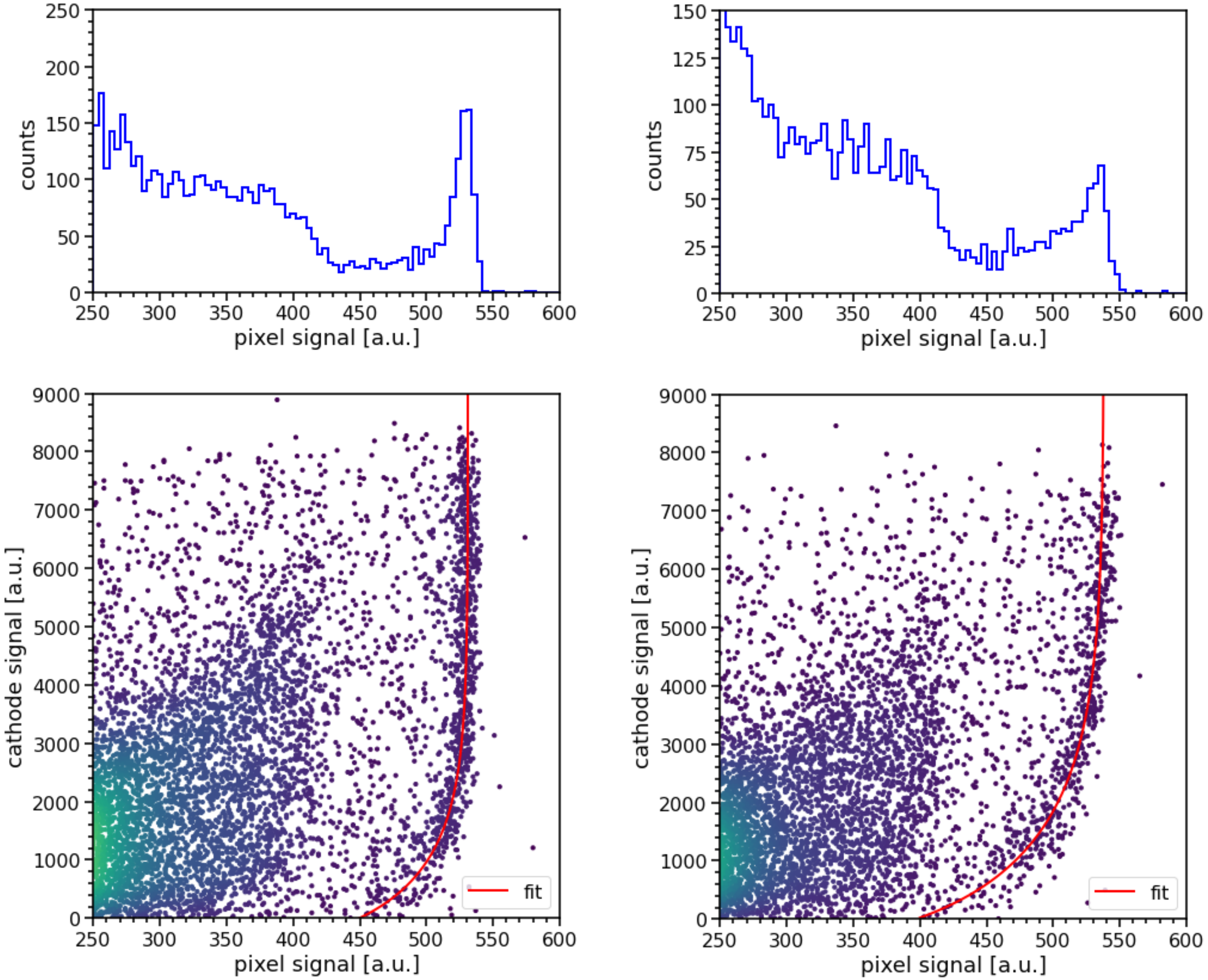
COMPTEL data from [Schönfelder, *New Astron. Rev., 48* (2004)]
INTEGRAL-SPI from [Roques et al., *A & A*, 411 (2003)]
INTEGRAL-IBIS from [Ubertini et al., *A & A*, 411 (2003)]

Experimental set-up



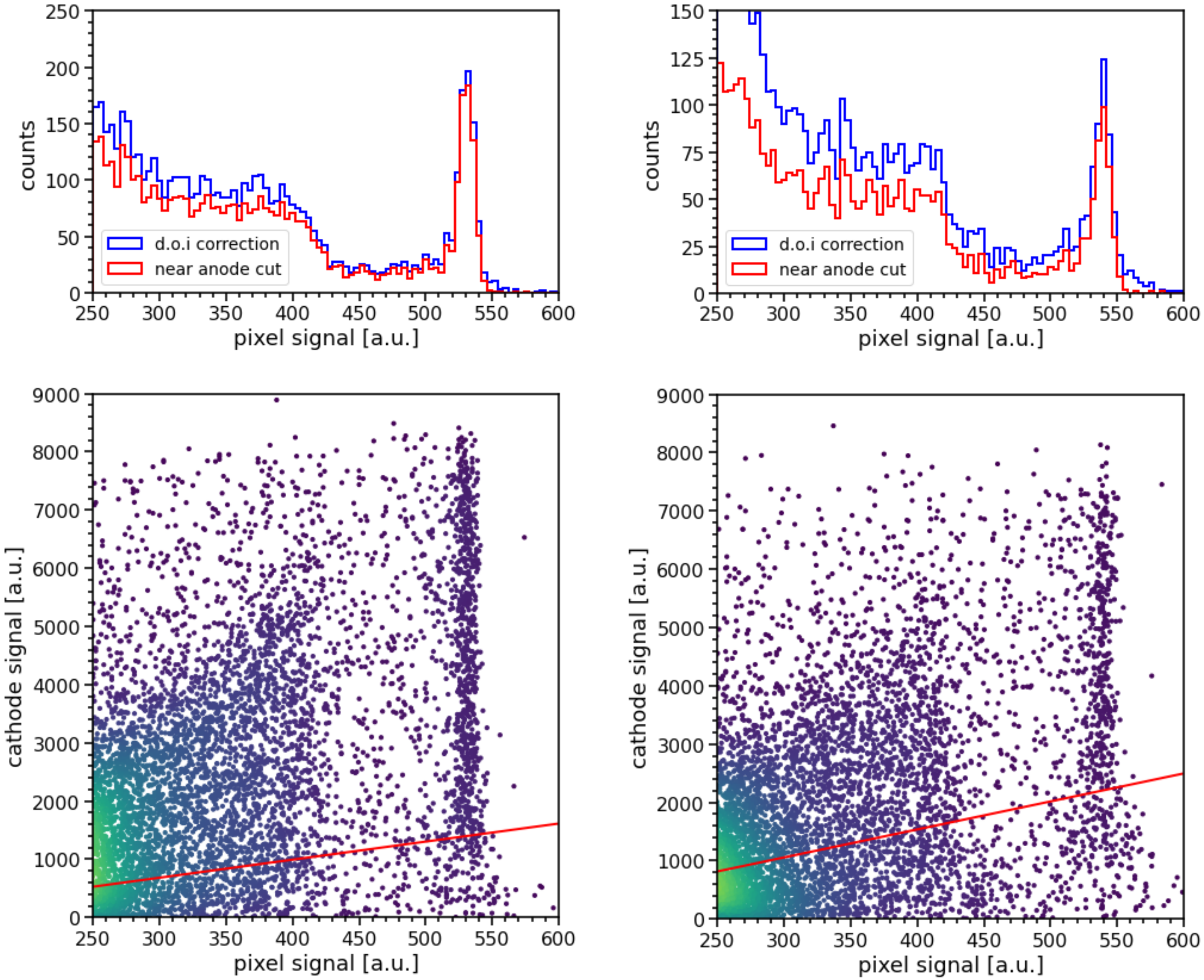
- Performance of pixelated CdZnTe detector tested with different radioactive sources.
- Anode read-out: 64-channel VATA450.3 ASIC by *Ideas.* Meets our requirements in terms of dynamic range, noise, and power consumptions (0.25mW/ch)
- Preliminary cathode read-out: *Amptek A250F* charge sensitive pre-amplifier

Spectral performance: depth-of-interaction correction



- Energy spectra for the 662keV line of Cs-137: left tails due to incomplete charge collection and electron trapping
- Signals from the cathode, taken in coincidence with those of the anode electrodes, provide a correction for these effects (depth-of-interaction technique).
- Improvement of the energy resolution

Spectral performance: depth-of-interaction correction



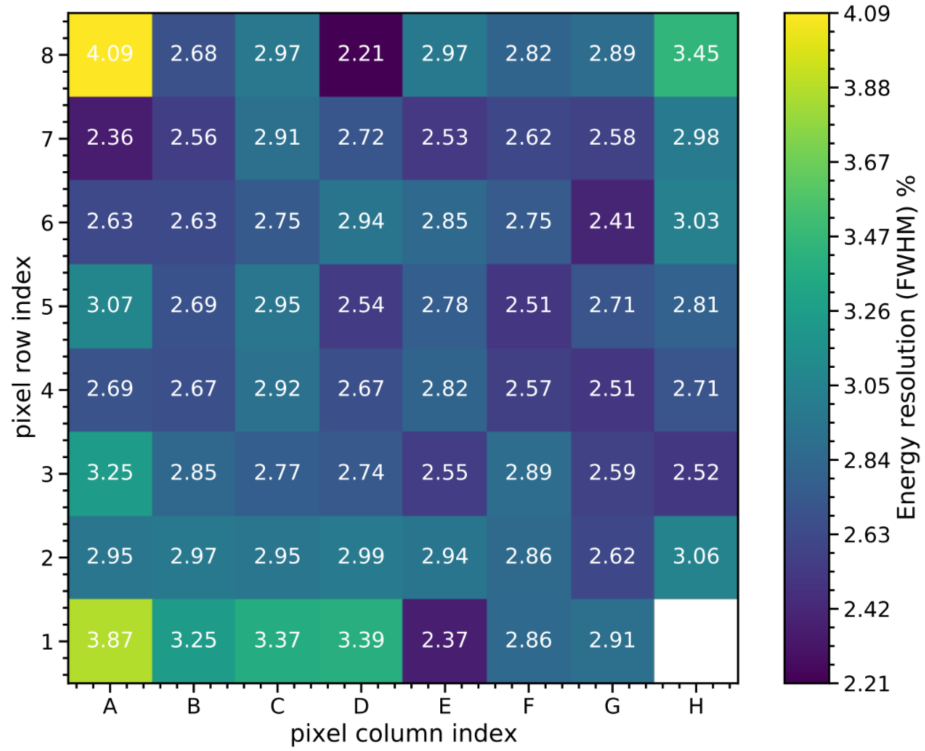
- Energy spectra for the 662keV line of Cs-137: left tails due to incomplete charge collection and electron trapping

- Signals from the cathode, taken in coincidence with those of the anode electrodes, provide a correction for these effects (depth-of-interaction technique).

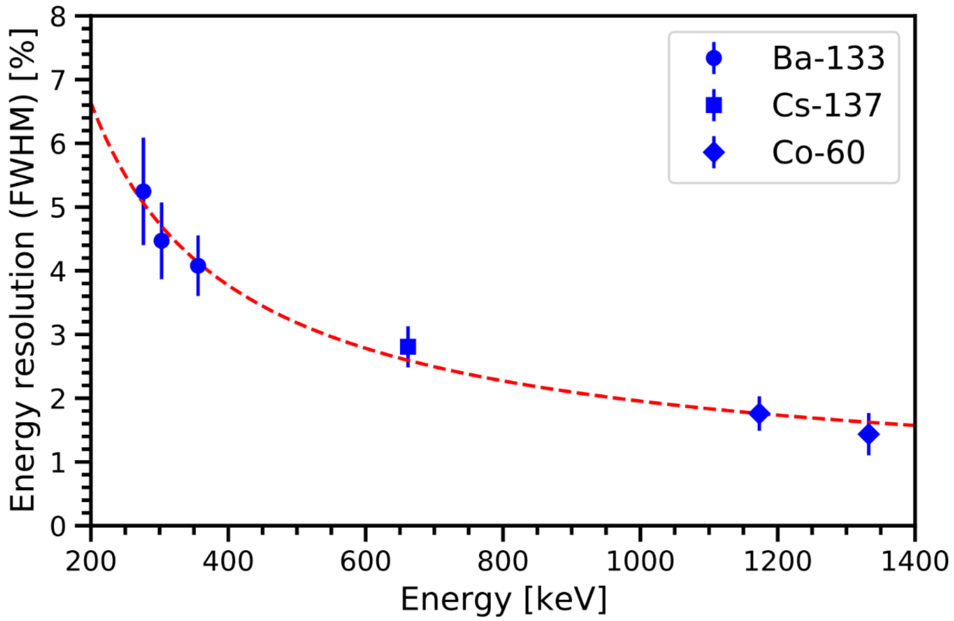
- Improvement of the energy resolution

- Removal of near-anode events further improves the energy resolution, but limits the active detector volume to $\sim 80\%$

Energy resolution



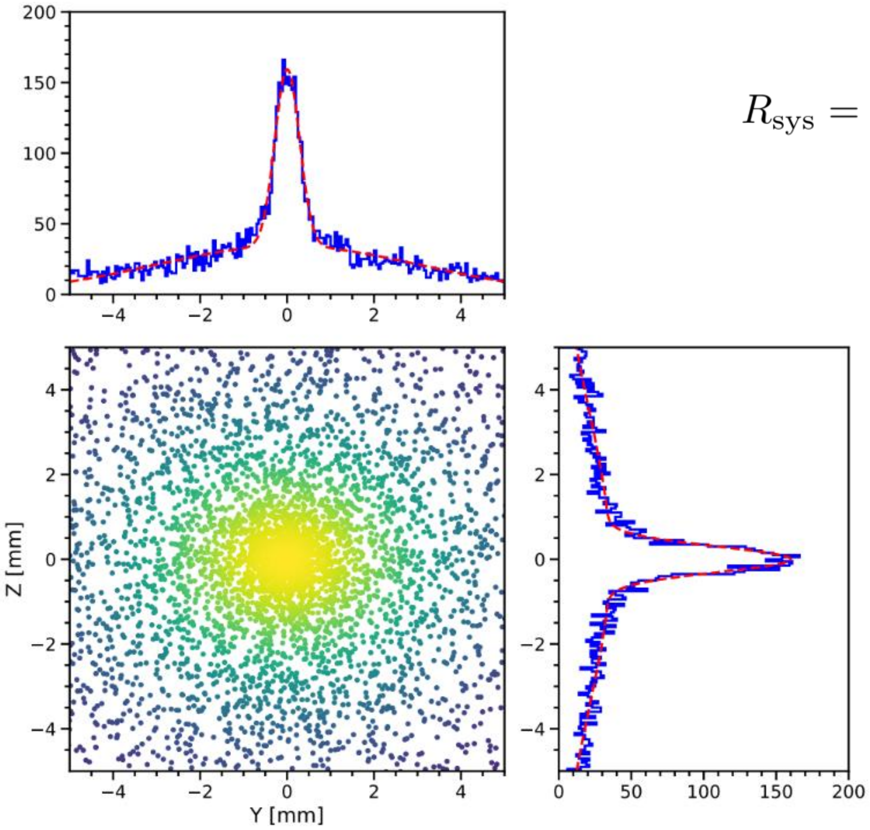
Energy resolution < 3% FWHM at 662 keV (Cs-137 line) for majority of pixels



Energy dependence: energy resolution is on average ~6.5% at 200 keV decreasing to <2% at energies above 1 MeV

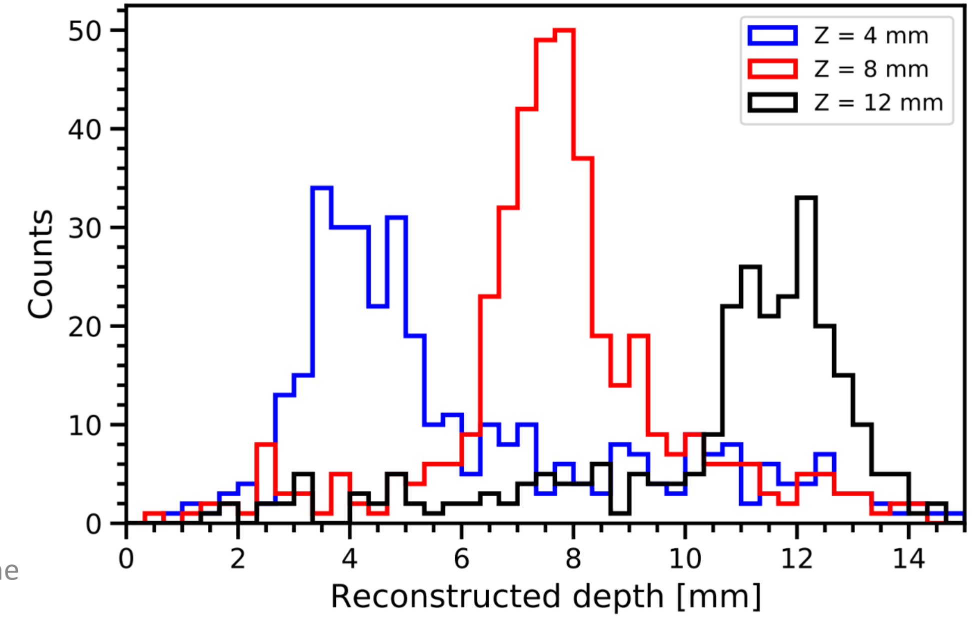
Spatial resolution

- Resolution on the detector plane (x-y axes) dictated by the pixel dimensions
- Interaction depth (z axis) measured from the ratio between the cathode and the anode signals
- Tested with Cs radioactive source + copper collimator. Geant4 simulation to define the “geometrical illumination spot”.
- Depth resolution below 2 mm (FWHM)



$$R_{\mathrm{sys}} = \sqrt{R_{\mathrm{det}}^2 + R_{\mathrm{c}}^2}$$

Collimator position [mm]	R_{sys} [mm] (FWHM)	R_{det} [mm] (FWHM)
4.0	2.10 ± 0.61	1.97 ± 0.64
6.0	2.07 ± 0.54	1.95 ± 0.58
8.0	1.79 ± 0.40	1.65 ± 0.43
10.0	1.88 ± 0.35	1.75 ± 0.38
12.0	2.05 ± 0.31	1.92 ± 0.33



Conclusions

- Evaluation of the viability and performance of a Compton telescope based on the CubeSat standard:
  - ✓ Angular resolution of 1.5°, field-of-view around 2sr, sensitivity comparable to the one achieved by the last generation of large satellites like COMPTEL and INTEGRAL
  - ✓ The combination of wide field-of-view, reasonable angular resolution and comparatively low costs make MeVCube a powerful instrument for observations of transients.
  - ✓ Future work might include dedicated studies on polarization measurement capabilities and sensitivity to nuclear lines

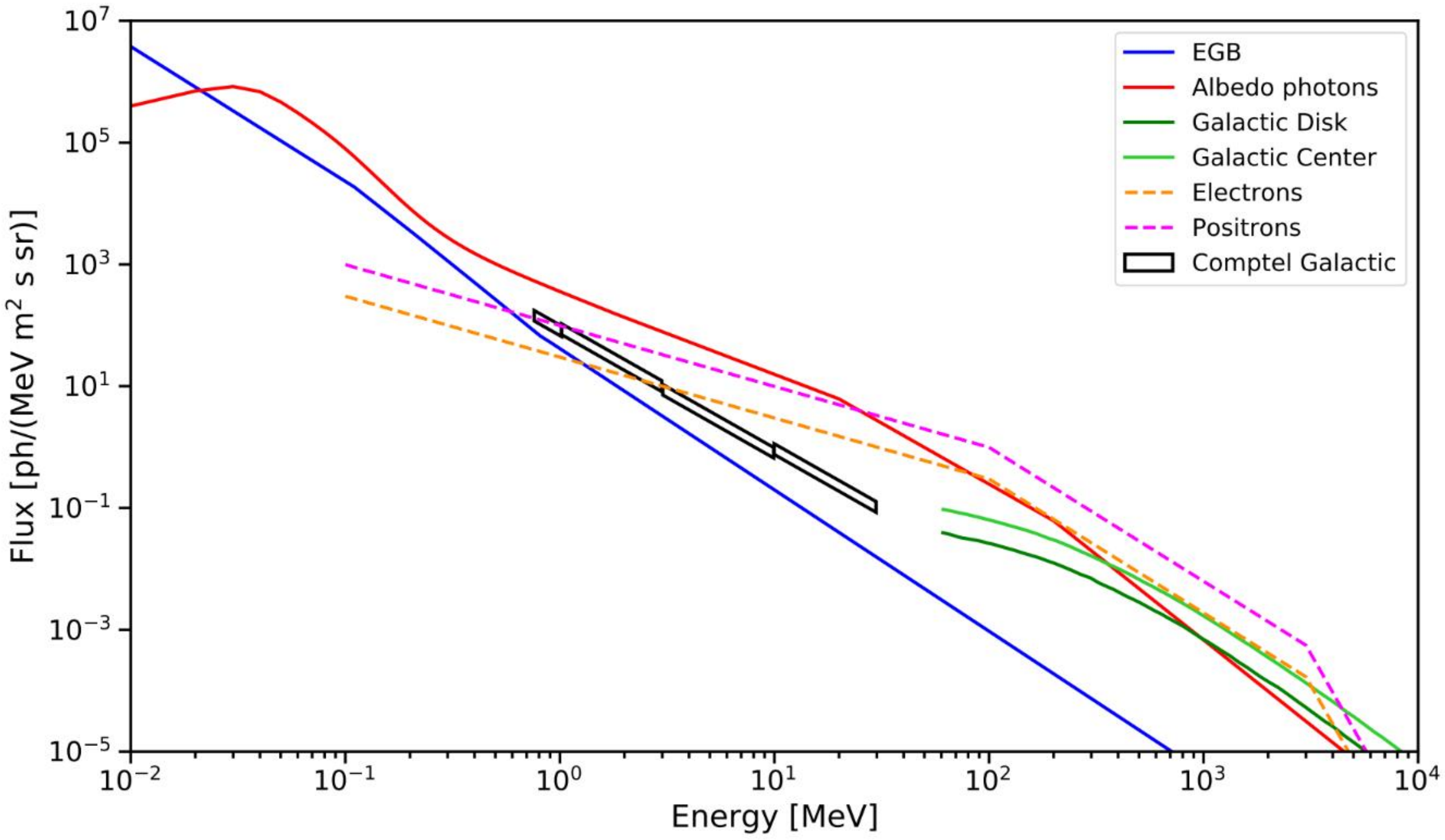
- Experimental measurements:
  - ✓ Evaluation of the read-out electronics and performance of custom design CdZnTe detector
  - ✓ Energy and angular resolution meets the requirements for the mission

- Successful proposal to DFG (DESY; David Berge, Markus Ackermann) and NSFC (IHEP; Peng Wen-Xi, Wan-Chang Zhang):
  - ✓ Development of a prototype Compton camera compatible with the 1U standard

Backup slides

MeV background

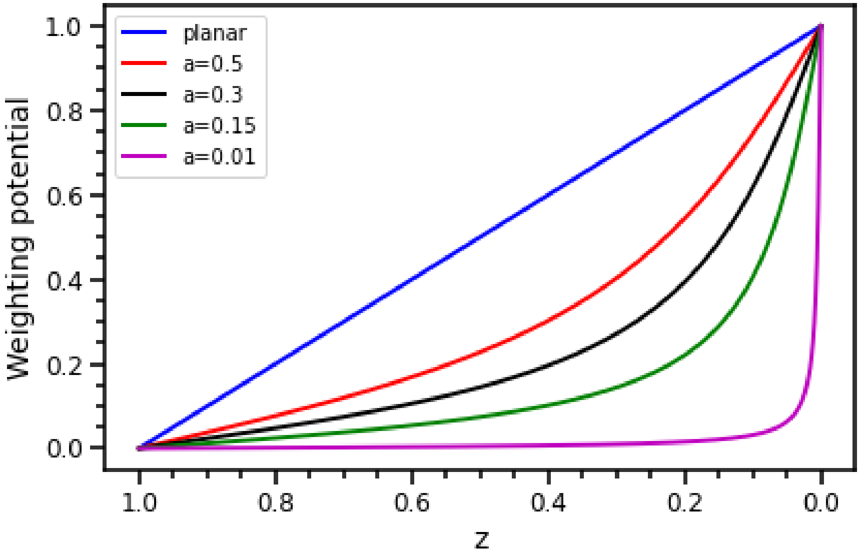
- *EGB:* diffuse and isotropic photon background due to unresolved sources
- *Albedo photons:* gamma-ray background produced by the cosmic rays interactions with the upper layers of Earth's atmosphere
- *Galactic emission*
- *Charged particle background:* charged cosmic-rays hitting the detector; vetoed by an ACD
- *Material Activation*



CdZnTe properties

Property	$Cd_{0.9}Zn_{0.1}Te$	CdTe	Si	Ge
Atomic number, Z	48, 30, 52	48, 52	14	32
Density, ρ [g/cm^3]	5.78	5.85	2.33	5.33
Band gap, E_g [eV]	1.57	1.44	1.12	0.67
Pair creation energy, E_{pair} [eV]	4.64	4.43	3.62	2.96
Resistivity, ϱ [Ω cm]	$3 \cdot 10^{10}$	10^9	$< 10^4$	50
Fano factor	0.09	0.11	0.12	0.08
Radiation length, X_0 [cm]	1.44	1.44	9.37	2.30
Electron mobility, μ_e [cm^2/V s]	1000	1100	1400	3900
Hole mobility, μ_h [cm^2/V s]	80 – 120	100	480	1900
Electron lifetime, τ_e [s]	$3 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$> 10^{-3}$	$> 10^{-3}$
Hole lifetime, τ_h [s]	10^{-6}	$2 \cdot 10^{-6}$	10^{-3}	$2 \cdot 10^{-3}$
$\mu_e \cdot \tau_e$ [cm^2/V]	$10^{-3} - 10^{-2}$	10^{-3}	> 1	> 1
$\mu_h \cdot \tau_h$ [cm^2/V]	$10^{-5} - 10^{-4}$	10^{-4}	~ 1	> 1

CdZnTe signal formation



Shockley–Ramo theorem:

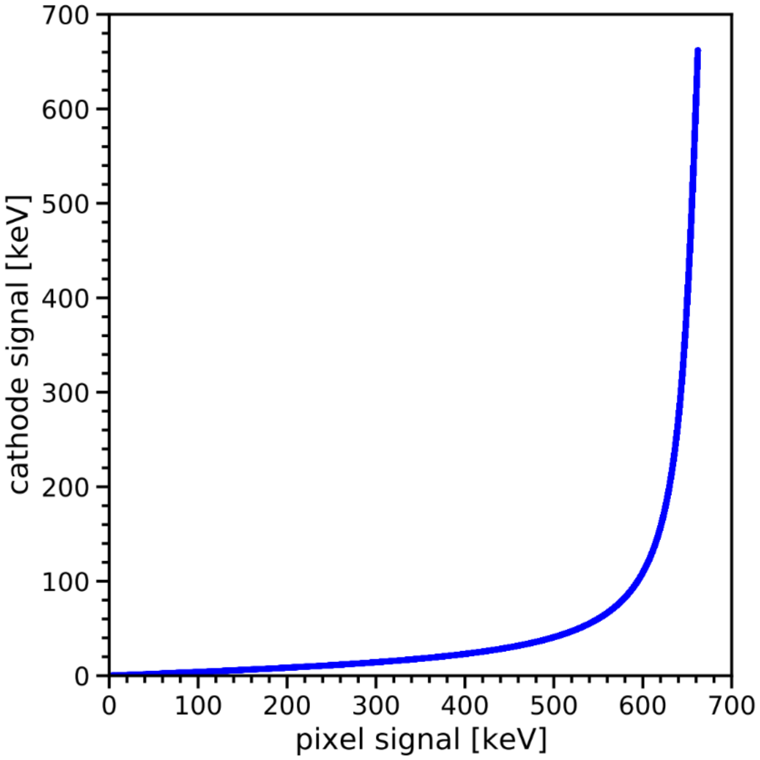
$$Q_i(\bar{t}) = \int_{t_0}^{\bar{t}} i_i(\vec{r}(t))\, dt = -\int_{t_0}^{\bar{t}} q\vec{E}_{w,i} \cdot \vec{v}(\vec{r}(t))\, dt$$

$$= -\int_{\vec{r}(t_0)}^{\vec{r}(\bar{t})} -q\vec{\nabla}\phi_{w,i}(\vec{r}(t))\, d\vec{r} = eN_0[\phi_{w,i}(\vec{r}(\bar{t})) - \phi_{w,i}(\vec{r}(t_0))]$$

Trapping in thick CdZnTe detectors:

$$q = q_0 e^{[r(\bar{t}) - r(t_0)]/\lambda}$$

$$\lambda = \mu\tau E$$



Effect of the steering grid

The effect of the steering grid is evaluated from the improvement in the detection rate of photo-peak events

$$\Delta\epsilon = \frac{\frac{N_{-50\text{V}}}{t_{-50\text{V}}} - \frac{N_{\text{floating}}}{t_{\text{floating}}}}{\frac{N_{\text{floating}}}{t_{\text{floating}}}}$$